CO_2 Sequestration and Enhanced Oil Recovery Potential in Illinois Basin Oil

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Abstract: General screening criteria developed from the West Texas CO_2 EOR experience were applied to Illinois Basin oil fields. Prior to including the depth criterion, nearly all Illinois oil reservoirs meet the criteria for successful CO_2 floods. The depth of the producing horizon was found to directly determine the miscibility condition. Each field in the Basin was classified as Miscible, Near-Miscible, or Immiscible based on field depth and the pressure-temperature relationship of CO_2. The oil reservoir assessment focused on the predominant producing horizons: the Mississippian Cypress and Aux Vases Sandstones and the Ste. Genevieve Limestone. Reservoirs from these horizons that had core analyses data, modern log suites, and complete waterflood records were selected for geological modeling for use in reservoir simulation.

A method for estimating CO_2 EOR and storage volume uses oil recovery and CO_2 storage factors, which are a function of the original oil in place (OOIP). Consequently, a rigorous review of the OOIP was undertaken, and the recovery and storage factors were quantified using a compositional simulator on geologic models of the fields. Deterministic methods were used to create structure maps for the geologic models, while geostatistical simulation was used to model the petrophysics.

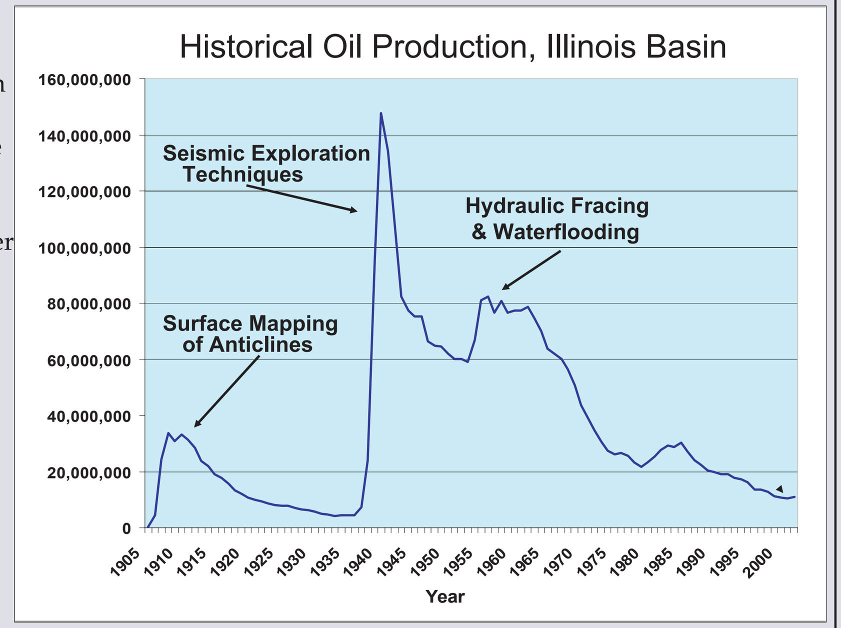
To determine the prime CO_2 EOR and storage targets in the Basin, a database analysis was used to combine the Miscibility Condition, OOIP, and recovery and storage factors. The selected geologic models and reservoir simulations of reservoirs representative of the most prolific formations more precisely define the CO_2 EOR and storage potential of the Basin.

Introduction:

- Using hydrocarbon-bearing strata for CO_2 sequestration provides potential value-added benefit
- New oil recovered from old oil fields
- CO_2 used for enhanced oil recovery (EOR) in West Texas and other areas
- West Texas CO_2 EOR experience suggests that flooding produces
  - Additional 10% of original oil in place (OOIP) or
  - Additional 25% beyond primary plus secondary production

History:

- Illinois Basin an active oil basin for more than a century
- Cumulative production to date more than 4.3 billion barrels
- Most fields in the basin in secondary production using water flooding
- Provides abundant candidates for CO_2 injection
- One test of CO_2 flooding to date



Focus:

- Potential of CO_2 flooding in Illinois Basin fields
- Estimate potential additional hydrocarbon recovery from CO_2 flooding
  - Requires updated estimate of basinwide OOIP
- Establish selection criteria for candidate fields
  - Analogs with West Texas experience
  - Geologic setting of the Illinois Basin.
- Validate hydrocarbon recovery estimates with reservoir simulation
- Calculate volume of sequestered CO_2

Original Oil in Place (OOIP) Calculation:

- Most recent estimate by Mast and Howard (1991)
  - Estimated basinwide OOIP 12 BSTB (billion bbl)
  - Estimated recovery potential of 36% 4.32 MMBO (primary plus secondary production)
- 4.3 BSTB produced to date, current annual production approximately 12 MMSTB (million bbl)

Historical Production:

- Fifty different producing horizons
- Approximately 78% of production from Middle Mississippian Chesterian strata
- Studied most prolific formations: Cypress and Aux Vases Sandstones and Ste. Genevieve Limestone

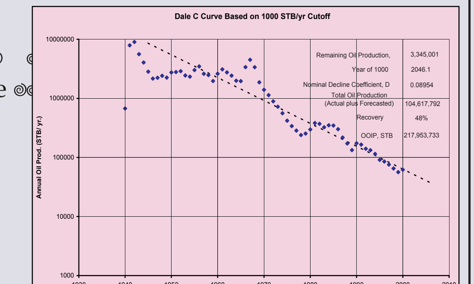
Procedure:

- Computer analysis of data derived from Arc-GIS and Access database
- The analysis uses standard volumetric OOIP formula, expressed as

$$OOIP = Ah\phi(1\text{-}S_W) / B_O$$

- A = reservoir drainage area: calculated in Arc from buffer area around producing wells
- h = reservoir thickness: from survey well and production databases
- ϕ = reservoir porosity: from survey well and production databases
- S_W = reservoir water saturation: state survey observation (45% in IL, 35% in IN & KY)
- B_O = oil formation volume factor: estimate of 1.15 for medium-gravity crude oil

- Estimate made for each field
- Estimated OOIP checked against cumulative production with mean 36% recovery factor using decline-curve analysis in large fields with good production data



Results:

- Revised estimate of basinwide OOIP is 14.1 BSTB
- Increase of 17.5% over the previous estimate

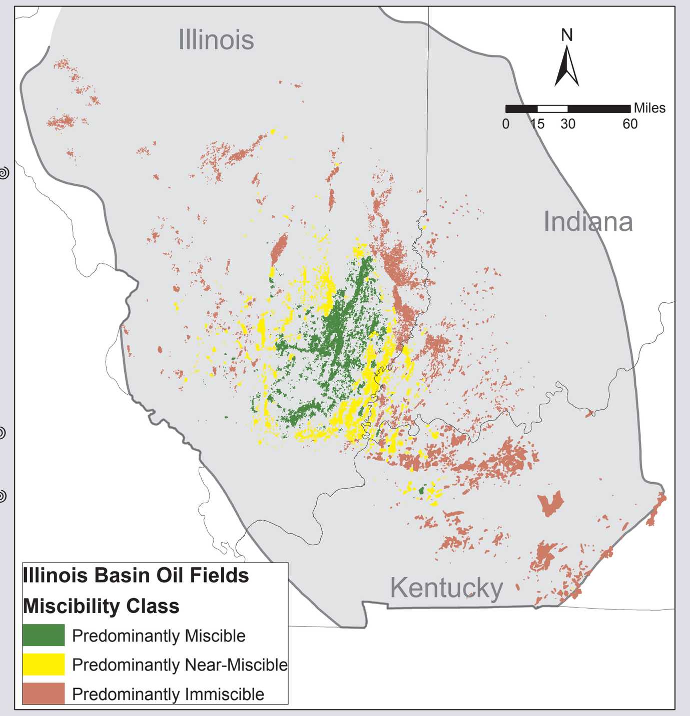
Classification of Reservoirs on Basis of CO_2 Miscibility:

Predicted Oil Field Conditions:

- Oil field depth: reservoir bulk volume weighted depth
- Pressure: fresh water gradient (0.433 psi/ft)
- Temperature: representative geothermal gradient 1.0°F/100 foot; datum of 62 °F @ 100ft

Miscibility Classification:

- Calculated oil field p&T conditions compared to p-T phase diagram and isochor of pure CO_2
- Depth to miscible/immiscible boundary based on combination of p&T gradients
  - Critical p&T for CO_2 is 1073 psia and 87.8°F
  - Basin temperature gradient estimated between 1.0°F/100 foot and 1.2°F/100 foot
  - Pressure based on allowable waterflood injection pressure,
    - 0.8 psi/foot (IL, IN)
    - 0.733 psi/foot (KY).
    - Lower limit of 0.433 psi/foot
  - Minimum depth to boundary approximately 2100 feet
  - Maximum depth to boundary approximately 2900 feet
- Output map groups fields based on weighted average depth (D) to producing horizon
  - Predominantly immiscible where D < 2100 feet (red)
  - Predominantly Im/Miscible where 2100 < D < 2900 feet (yellow)
  - Predominantly miscible where D > 2900 feet (green
- Prior work by Korose, et al. (2004)



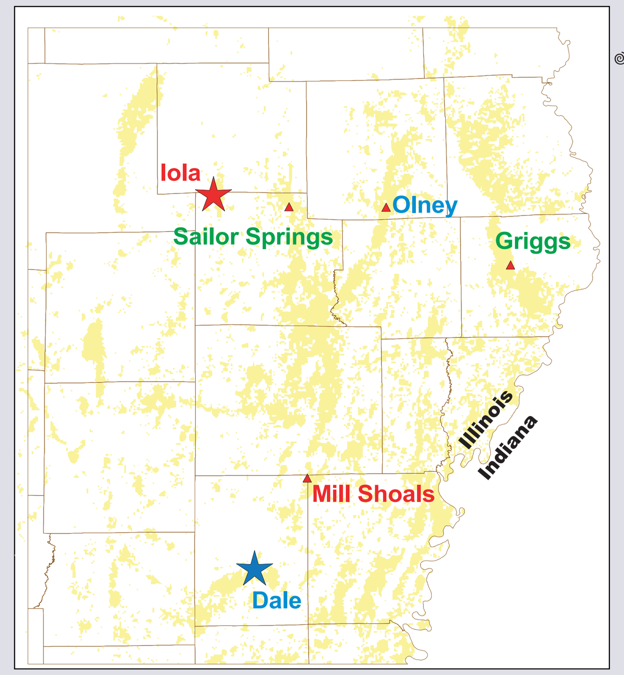
After Korose, *et al.* (2004)

Other Selection Criteria:

- Oil viscosity, API gravity, and crude oil composition
- Almost all Basin oil viscosity and gravity meet the screening guidelines
- Insufficient oil composition data to compare to the composition rule-of-thumb for CO_2 EOR.

Field Studies:

- Selection based on miscibility/immiscibility, location, and data quality
- 190,000 wells in Illinois portion of the basin
  - 100,000 with wireline log(s)
  - 12,000 with some form of porosity log
  - Most have only SP and resistivity logs
- Essential data type is core analysis
- Modern porosity logs rare in waterfloods
- Target formations have some 3100 cores
  - Analyses of permeability and porosity
- Studies sited on clusters of cores
- Six fields chosen; two from each target zone



Six of the Illinois Basin fields selected for preliminary modeling. Fields are color-coded by producing formation as follows: Ste. Genevieve Limestone, Aux Vases Sandstone, Cypress Sandstone. Locations of example fields (Iola & Dale) marked by stars.

Geological Modeling:

- Used GeoGraphix Suite of applications
- Log- and core-based zones identified
- Compare log traces to core measurements
- Maps of structure and isochore generated for each zone

Geostatistical Modeling:

- Used Isatis geostatistical modeling software
- Stochastic geostatistical technique produces three-dimensional visualizations of porosity and permeability.
- Structure grids used as spatial constraints,
- Variograms reflecting regional and local geological trends constructed and modeled
- Each scenario comprised thirty visualizations
- P_{50} realizations of porosity and permeability submitted to reservoir simulation

Reservoir Modeling:

- Uses Landmark Graphics Corporation's VIP compositional reservoir simulation software
- Models of primary and waterflood production qualitatively checked
- Predictive modeling of CO_2 flooding for EOR

Geological Modeling Example: Dale Field

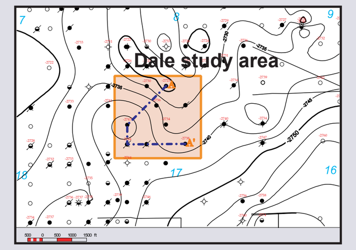
- Typical production from McClosky member of the Ste. Genevieve Limestone
- Reservoir bodies are homogeneous oolite shoals
- Reservoirs form *en echelon*, often stack, and may coalesce
- Typically less than ten feet thick, one-fourth mile wide and two miles long
- Abundant original intergranular porosity with permeabilities of up to 2 D
- Shoals drain and waterflood with recovery of more than of 50% of OOIP

Dale study area:

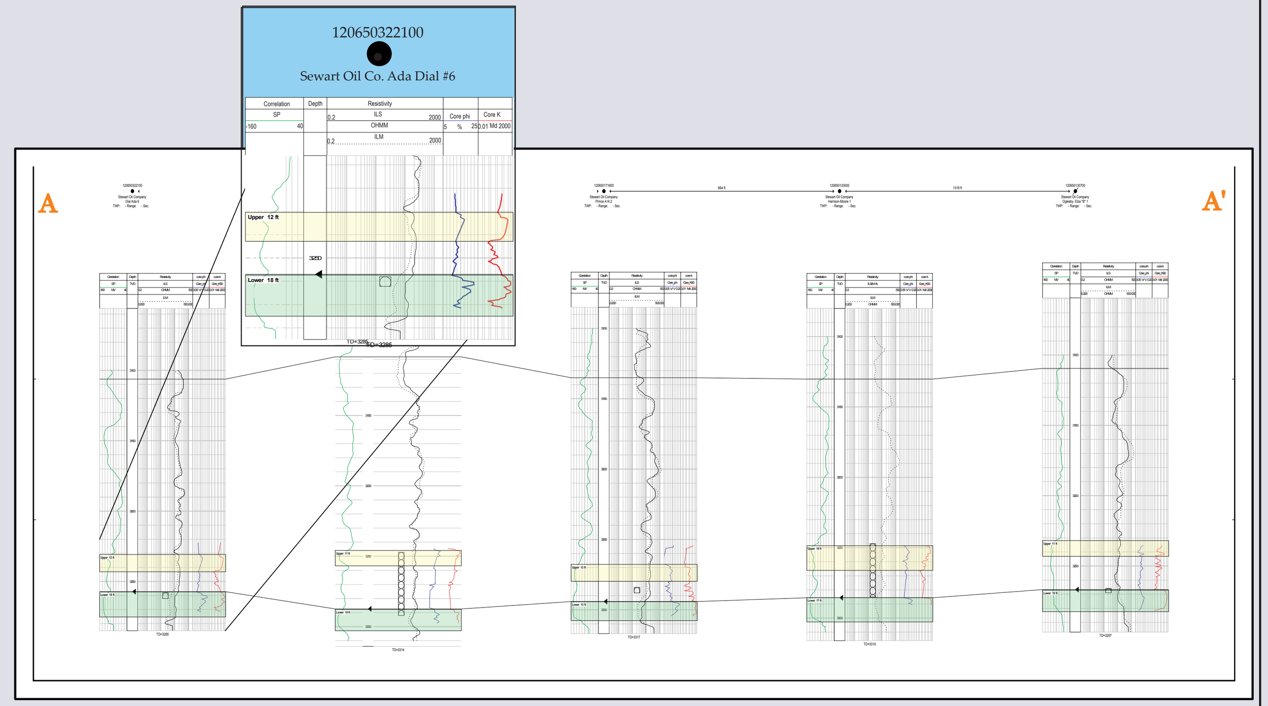
- Approximately two hundred acres of the larger Dale Field
- Two reservoir bodies identified from core data
- Measured horizontal permeability exceeds 1.6 Darcy
- Porosity rarely exceeds 20%.
- Porosity and permeability of non-reservoir rock encasing shoals much lower

Data:

- Five cored wells, 165 porosity and permeability measurements
- Two wells with wireline logs, no core
- One well with neither core nor log

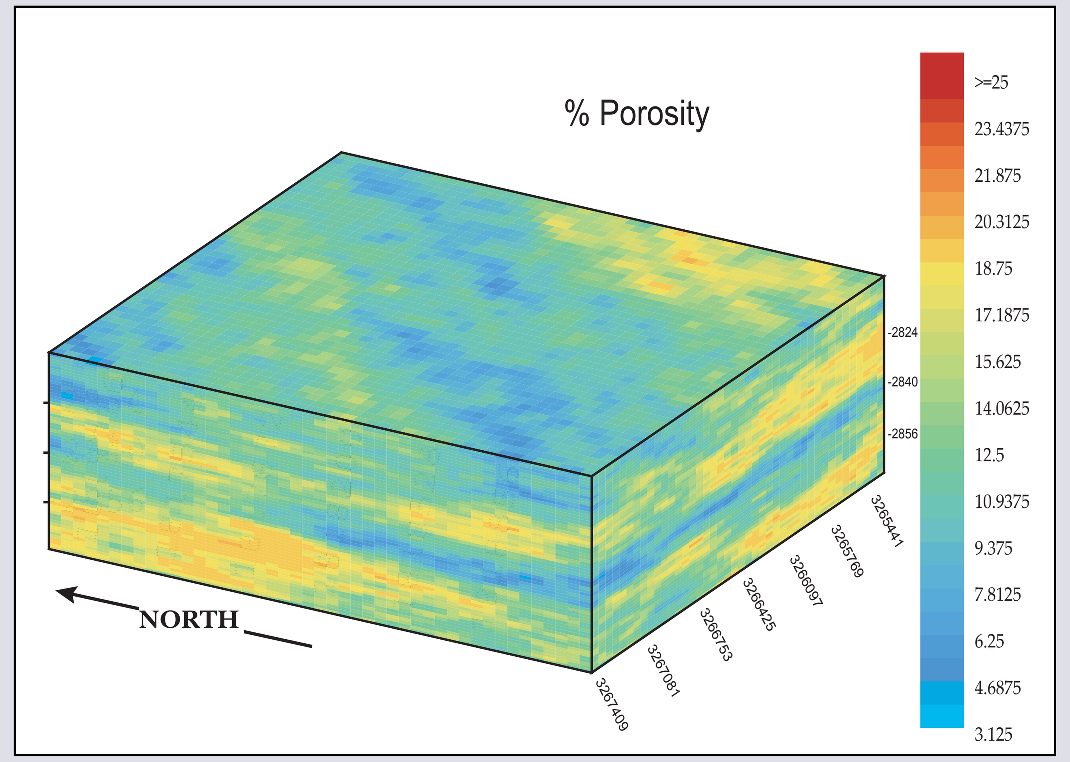


Dale study area marked by shaded box, line of cross section A-A' in blue. Contoured on top of Ste Genevieve Limestone (contour interval five feet, datum = MSL).

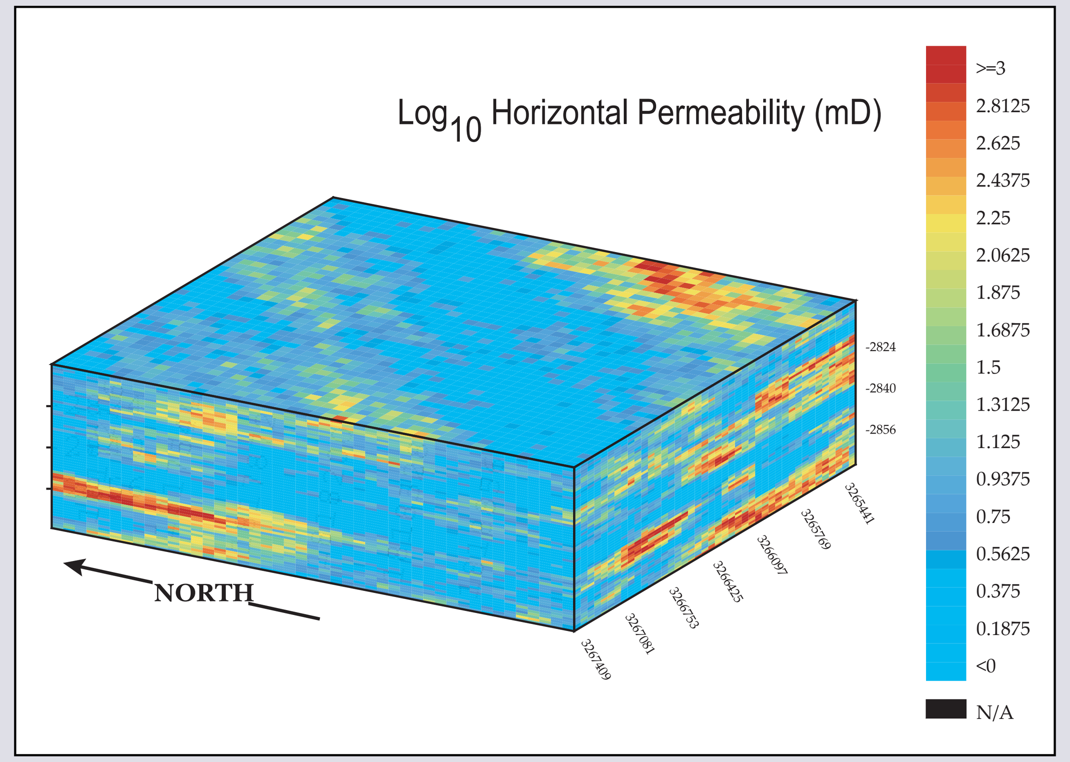


Structural cross section A-A' (see location map) through study area in Dale field, Hamilton County, IL, showing cored wells used to build geostatistical models. Log suite includes SP (track I), resistivity (track II), porosity (track III) and $\log_{10}$ permeability (track IV). Two stacked high-porosity and -permeability oolitic shoals are represented by the intervals shaded yellow and green.

Geostatistical Modeling Example: Dale Field



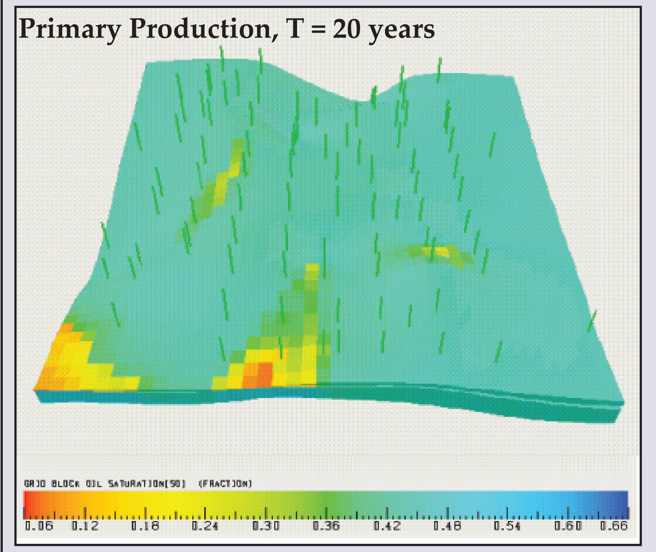
Isatis™ 3-Dimensional visualization of the Dale field study area. This core-derived porosity model was produced using turning band simulation. The display shown is the P_{50} realization of a set of thirty simulations. The variogram used in the scenario was a nested anisotrophic nugget and spherical combination. Original data comprised 165 measurements from five cored wells (see cross section). View looks from the southwest at an elevation of 20° above horizontal.

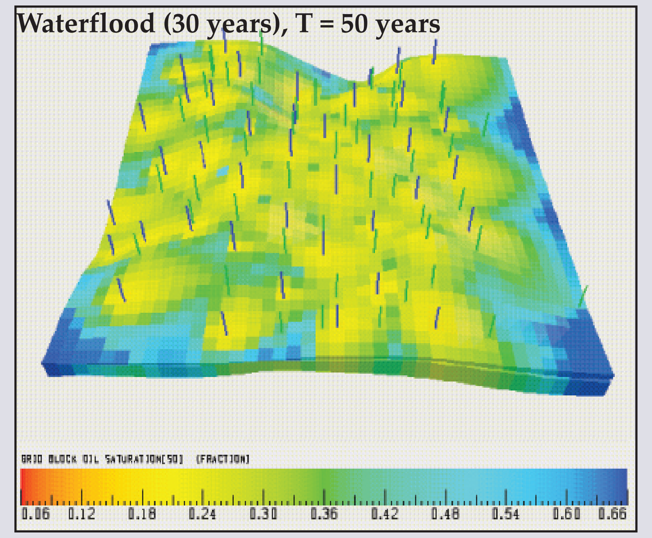


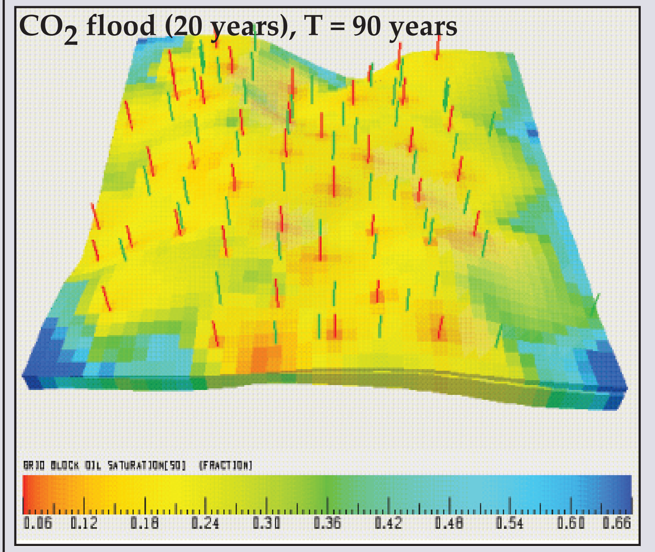
Isatis™ 3-Dimensional visualization for the Dale field study area. This $\log_{10}$ core-derived horizontal permeability model was produced using co-located cosimulation employing the Markhov-Bayes Assumption. The display shown is the P_{50} realization of a set of thirty simulations. The variogram used in the scenario was the same variogram used in the porosity model. Original data comprised 165 measurements from five cored wells (see cross section). View looks from the southwest at an elevation of 20° above horizontal.

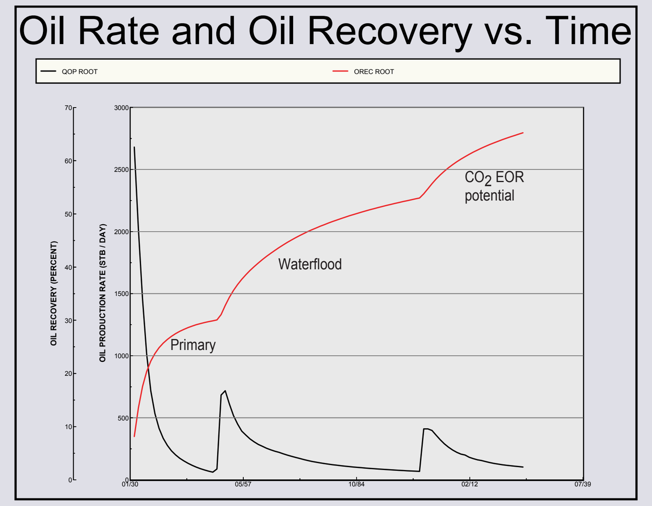
Reservoir Modeling, Iola Field (Cypress Sandstone)

- Geologic and reservoir models intended to generally represent specific geologic formations within the Basin (Cypress, Aux Vases, and St. Genevieve)
- Recovery and storage factors estimated from models to be applied basin-wide using GIS and databases
- Equation-of-state, compositional reservoir simulation used to simulate primary, waterflood, and CO_2 flood









Model Results (Iola Field Simulation):

- Three-dimensional three-layer model with vertical communication
- Three-component Peng-Robinson equation-of-state
- Vertical lines represent well locations (water injectors coded blue, CO_2 injectors coded red)
- Vertical axis exaggerated, model is relatively flat
- 50 - 55% oil recovery from primary production and waterflooding
- Additional 10-12% CO_2 EOR beyond primary and waterflooding

Geologic Model composed of Deterministic (structure and thickness) and Probabilistic (porosity and permeability) components. The Geologic Model data is then incorporated into a Reservoir Flow-Reservoir Simulation Model to determine capacity of reservoir for CO_2 EOR and CO_2 storage.

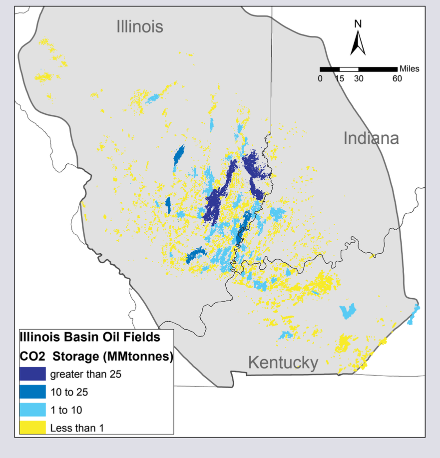
Simulation Model of Iola Field incorporates 20 years of primary and 50 years of secondary waterflood production followed by 25 years of CO_2 injection.

Plot shows the potential for an additional 15% recovery with CO_2 EOR.

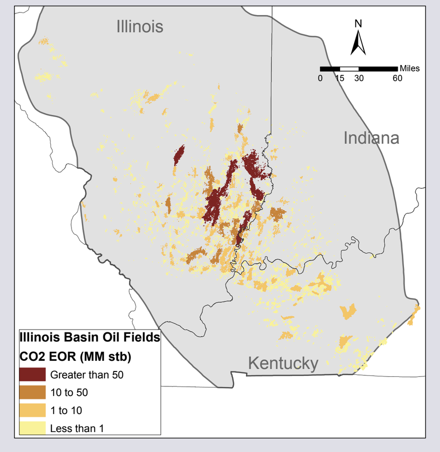
Conclusions

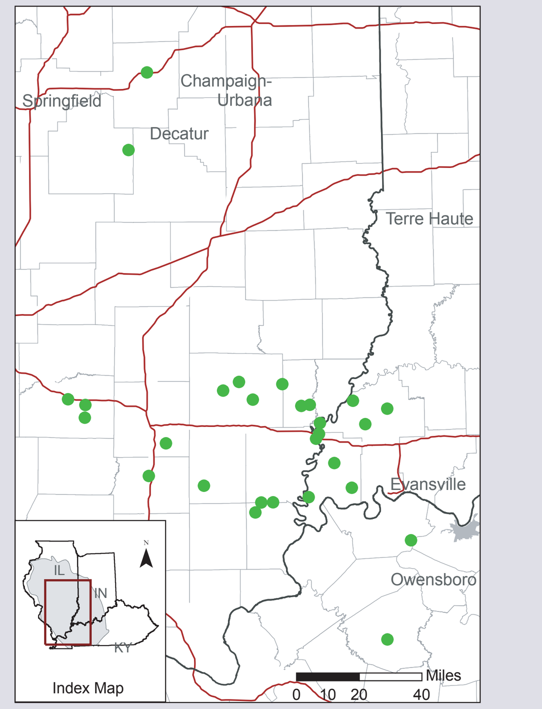
- Additional 2.1 BSTB Original Oil in Place estimated from volumetric study
- Using West Texas rules of thumb
  - Predicted CO_2 EOR ranges from 0.71 to 1.6 BSTB
  - CO_2 storage capacity is 190 to 870 MMtonne
- Cypress, Aux Vases, Ste Genevieve, and rocks of similar age represent 78% of total basin production
- 46% of OOIP is miscible and near-miscible

Distribution and Capacity for CO_2 Storage of Potential Oil Field Sinks, Illinois Basin



Distribution of Sites and Potential CO_2 Enhanced Oil Recovery from Oil Fields, Illinois Basin





Current site selections based on distribution of miscible and immiscible potential CO_2 EOR floods and cooperative field operators. Includes two potential liquid CO2 floods as a result of relatively low temperature and high pressure.

Acknowledgments:

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